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## Phase Doppler Measurements in Dense Sprays

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### Abstract

Measurements of droplet size, velocity and volume flux have been made in a dense spray using phase Doppler interferometry. Volume flux measurements have shown significant improvement over conventional phase Doppler techniques through the use of a flow splitter which provided the probe beams and scattered light signals access to the dense core of the spray. Also, the beam waist diameter was made much smaller than the droplets being measured in order to reduce multiple particle occurrences within the probe volume. The volume flux measurements were very encouraging when compared to measurements made with a mechanical patternator.

### Introduction

Optically dense sprays, which are usually encountered at high chamber pressures, present an extremely challenging environment for laser diagnostic measurements. Unfortunately, laser diagnostic techniques for measuring droplet size, velocity and volume flux generally do not work well in dense sprays where droplet number densities,  $N$ , can reach  $10^5 \text{ cm}^{-3}$ , and light transmission rates through the spray,  $I/I_0$ , fall below  $10^{-4}$ . Laser diffraction techniques generally require that  $I/I_0$  be greater than  $10^{-1}$  in order to avoid errors associated with multiple scattering, while phase Doppler interferometry usually requires that the droplet number densities are less than  $10^3 \text{ cm}^{-3}$  in the size range of 5-300  $\mu\text{m}$ .

Of these two diagnostic approaches, the most promising for dense spray applications is phase Doppler interferometry. In this technique, droplets passing through a probe volume formed by the intersection of two laser beams scatter light which is imaged by a collection lens onto a pair of detectors. The droplet acts as a lens which magnifies the fringe pattern formed by the intersecting laser beams. The detectors measure the magnified fringe spacing as a temporal phase shift, which is linearly dependent on droplet size. There are several problems associated with making phase Doppler measurements in dense sprays. These include; multiple

particles present in the probe volume; probe beam and scattered light signal attenuation and; stray light reaching the collection optics due to multiple scattering.

Very little work has been done in the past in regard to dense spray diagnostics. Bachalo *et al.* [1] demonstrated the use of a phase Doppler particle analyzer (PDPA) in a gas turbine injector spray with peak droplet number densities of about  $8 \times 10^3 \text{ cm}^{-3}$ . The volume flux measured with the PDPA agreed very well with the volume flux measured with a collection tube. The reported number densities, however, are far less than those being considered in the present study. Sankar *et al.* [2] have used a PDPA in a shear coaxial rocket injector spray similar to the type of injector used in the present study. Peak number densities of about  $2 \times 10^4 \text{ cm}^{-3}$  were measured. It was also reported that the measured volume flux decreased with increasing gas flowrate through the injector which was attributed to evaporation of the smaller droplets. Evaporation, however, is unlikely to cause a significant decrease in measured volume flux because most of the volume in the spray is carried by the larger droplets which evaporate much more slowly.

### Description of the Problem

#### Multiple Particles in the Probe Volume

Phase Doppler interferometry requires that only one droplet be present in the probe volume at any given time. As the droplet number density increases, the probability of finding more than one particle in the probe volume also increases. Sankar *et al.* [3] have shown that the Doppler signal analyzer (DSA), which is a frequency based processor, is capable of measuring one of several particles present in the probe volume. The DSA cannot, however, account for the other particle(s) present in the probe volume. The result can be a severe underestimation of the particle number density and volume flux and a potential biasing of the particle size distribution. In order to avoid having more than one particle present in the probe volume, the probe volume must be decreased in size for dense spray applications.

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The authors have demonstrated in a separate paper being presented at this conference, that the probe diameter can be made much smaller than the largest droplet being measured by using an intensity validation technique which limits the minimum scattering intensity to one tenth the maximum intensity in each particle size class [4]. This insures that trajectory dependent scattering errors are avoided. A probe volume correction (PVC) which accounts for the decreased probe volume size is also used with the intensity validation scheme. The results have been encouraging in terms of volume flux measurements in dilute sprays.

#### Signal and Beam Attenuation

A second problem associated with dense spray measurements is attenuation of both the scattered light signal and the probe beams due to the droplets in the vicinity the probe volume. The degree of attenuation is a function of both the droplet number densities and the path length through the spray. Laser transmission rates through dense sprays can typically be less than  $10^{-4}$ . The loss in signal, however, can usually be overcome by increasing the intensity of the probe beams or by increasing the photomultiplier tube (PMT) voltage. The latter method does, however, decrease the signal-to-noise ratio in the scattered light signals due to increased shot noise from the PMTs. Beam drop out can occur when a particle on the order of the laser beam diameter passes through one of the probe beams. This is generally not a problem because the largest droplet number densities usually occur at droplet sizes smaller than the probe beam diameter.

#### Multiple Scattering

The issue of multiple scattering is several-fold. The scattered light signal originating from a droplet in the probe volume is re-scattered by droplets which lie between the probe volume and the receiving optics. The phase shift of the re-scattered light will be different from that of the originally scattered light. If enough secondary scattering events occur, the original phase information may be lost, in which case the instrument will probably reject the measurement.

A second type of multiple scattering phenomena occurs when droplets pass through the path of the probe beams, but outside of the probe volume. These particles will scatter light which may be re-scattered by droplets in the line of sight of the receiving optics, as illustrated in Figure 1. This scattered light signal, which contains no phase information, can trigger the detector gate and cause the gate to remain triggered for long periods of time thus missing particles that are actually in the probe volume. This problem is the most serious of the multiple scattering problems and is often seen as an increased background noise level. If the

droplet number densities are large enough, the gate may remain continuously triggered because there is always some scattered light reaching the PMTs.

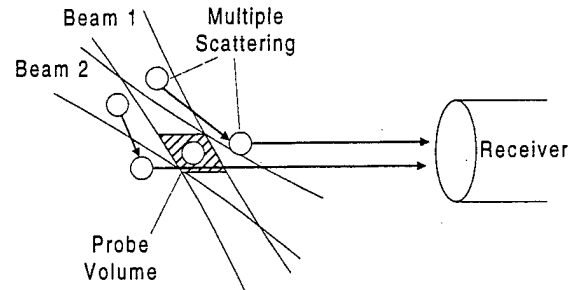


Figure 1: Illustration of multiple scattering.

A sample of the oscilloscope traces of the scattered light signals and the corresponding detector gate from a dense spray are shown in Figure 2. This sample was taken with a beam waist diameter,  $D_w$ , of 350  $\mu\text{m}$ , and a slit width,  $D_s$ , of 100  $\mu\text{m}$  in a spray with a droplet number density of about  $4 \times 10^4 \text{ cm}^{-3}$ .

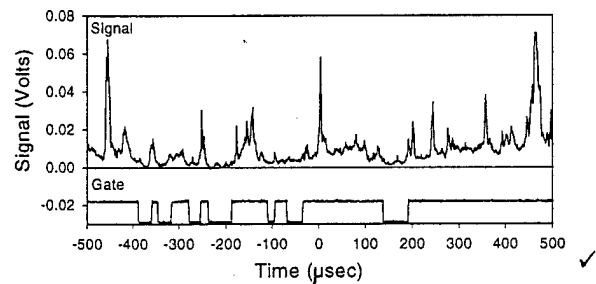


Figure 2: Oscilloscope trace of signal and gate.  $P_c=0$  psig,  $\text{H}_2\text{O}=18.9$  gm/s,  $N_2=3.17$  gm/s,  $Z=50$  mm,  $R=0$  mm. Beam waist,  $D_w=350 \mu\text{m}$ , slit,  $D_s=100 \mu\text{m}$

Figure 2 demonstrates the overlapping signals which are due to both multiple particles within the probe volume and multiple scattering from particles outside of the probe volume. This problem is partially alleviated by decreasing the probe diameter, which not only decreases the probability of multiple particle occurrences within the probe volume, but also decreases the probability of finding a particle in the beam path outside of the probe volume. Due to limitations in the processing electronics which require a minimum number of samples for processing, and thus a minimum transit time through the probe volume, the probe beams can not be made arbitrarily small and there will always

be droplets in the path of the probe beams. In order to overcome this problem, intrusive devices such as flow splitters must be used to reduce the path length of both the probe beams and the scattered light signals. Although even a well designed flow splitter may impart some disturbance to the flowfield, the tremendous increase in measurement confidence far outweighs the effect that the flow splitter has on the flowfield.

### Experimental Setup

The experiments were carried out at the AFRL cold-flow injector characterization facility which contains a windowed chamber rated to 13.8 MPa. The chamber contains a mechanical patternator consisting of 27 square, 6.35 mm tubes arranged in a linear array. The patternator is used to make volume flux measurements which can be compared to the results obtained with the PDPA. Water and nitrogen are used as simulants for LOX and  $\text{GH}_2$ . The injector being investigated is a single shear coaxial element of the type used in the space shuttle main engine fuel preburner. Water is injected through the central post of the injector while gaseous nitrogen is injected through a surrounding co-annular region. The PDPA used in this study was a standard 2-component fiber optically coupled, DSA based system manufactured by Aerometrics, inc. The focal length of the transmitter and receiver was 500 mm and the receiver was oriented at a forward scattering angle of  $30^\circ$ . The beam intersection angle was  $2.70^\circ$ . Beam waist diameters of 350  $\mu\text{m}$ , 172  $\mu\text{m}$  and 60  $\mu\text{m}$  were tested. The beam waist was varied by using a beam expander located inside the transmitter which increased the diameter of the laser beams and thus decreased the diameter of the beam waist.

### Flow Splitter

The flow splitter, which was designed to reduce the path length through the spray is illustrated in Figure 3. In an effort to determine the effect of the flow splitter on the flowfield, a series of experiments was conducted in which the spacing of the splitter plates was varied while the axial velocity, droplet size and volume flux were measured with the PDPA. The optical configuration of the PDPA included a beam waist diameter of 60  $\mu\text{m}$  and a slit size of 50  $\mu\text{m}$ . These experiments were conducted outside of the chamber at atmospheric pressure. The water flowrate was 18.9 gm/sec and the nitrogen flowrate was 3.17 gm/sec, which produced a moderately dense spray. Measurements of mean and rms axial velocity, volume flux and also laser beam transmittance through the spray as a function of splitter separation distance are shown in Figure 4. All measurements were made at 50 mm from the point of injection at the centerline of the spray.

Figure 4a shows a decrease in axial velocity as the splitter plate separation distance is decreased beyond about 4 mm. Some of the velocity decrease can be attributed to an increased count rate of smaller droplets which are traveling at a slower velocity, however, the flow splitter does appear to affect the flowfield for separation distances less than about 3 mm. The measured volume flux, as shown in Figure 4b increases as the splitter separation distance is decreased to about 3 mm. This is due to the increased "visibility" of the spray along with a decrease in the background multiple scattering signals which tend to falsely trigger the gate. Also shown in Figure 4b is the volume flux measured with a collection tube which shows that the peak PDPA measured volume flux is still about 14% lower than the collection tube measurement. Figure 4c shows the decrease in laser beam attenuation as the separation distance is decreased. From these experiments it was determined that for this particular spray, a splitter separation distance of about 3 mm yielded the best volume flux measurements while only having a small effect on the mean axial velocity of the spray. It should be pointed out that the effectiveness of any flow splitter will vary with the particular dynamics of the spray, especially if there are velocity components normal to the plane of the splitter plates which might tend to separate or block part of the flowfield of interest.

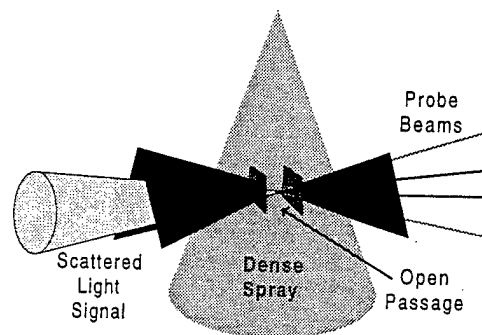


Figure 3: Schematic of the flow splitter orientation in a spray.

After determining the optimal splitter plate separation distance for the spray of interest, the flow splitter was fixed in space and the spray was radially traversed through the probe volume. A plot of the volume flux measured with the PDPA as a function of radial position compared to the volume flux measured with a collection tube is shown in Figure 5a. Note that these measurements are the combined result of using the flow splitter and the small probe volume with the intensity validation technique. The PDPA measurements agree fairly well with the collection tube measurements although the PDPA under-predicts the

volume flux slightly at the center of the spray where volume flux is greatest. Figure 5b is a plot of the droplet number density and the number mean diameter,  $D_{10}$ , as a function of radial position. The largest number densities actually occur in the outer region of the spray where the droplets are smaller in size and the volume flux and velocities are low.

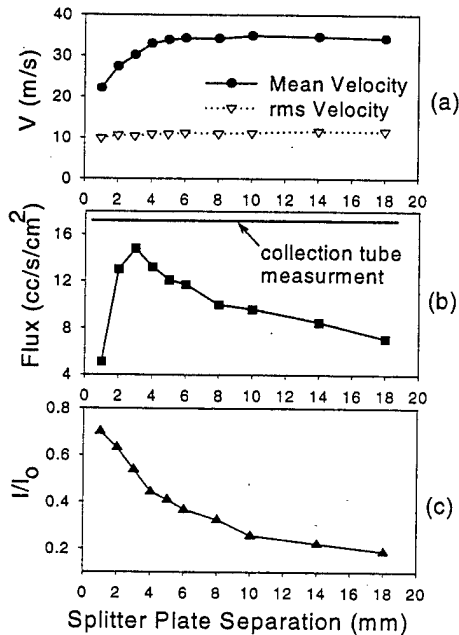


Figure 4: Effect of flow splitter on spray flowfield in a moderately dense spray at  $P_c=0$  psig. (a) mean and rms axial velocity, (b) volume flux, and (c) laser transmittance through spray.

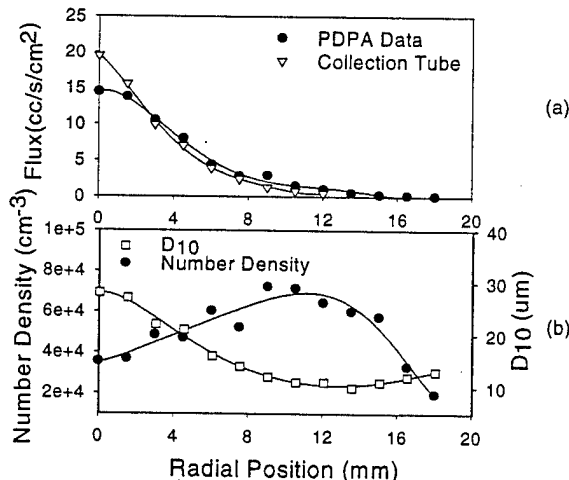


Figure 5: Radial profiles of (a) volume flux and (b) number density and  $D_{10}$  in a moderately dense spray at  $P_c=0$  psig.

### High Pressure Spray

A final set of experiments involved the same injector operating inside of the chamber at a chamber pressure of 2.9 MPa. The water flowrate was 32.7 gm/s and the nitrogen flowrate was 35.3 gm/s. All measurements were made at 50 mm from the point of injection and the flow splitter had a plate separation distance of 3 mm. Measurements of laser beam attenuation with and without the flow splitter revealed that the laser transmittance through the centerline of the spray was about  $10^{-4}$  without the flow splitter and  $10^{-1}$  with the flow splitter, thus demonstrating a large decrease in effective path length through the spray. The PDPA measured volume flux and the volume flux measured with the 27 tube mechanical patternator are shown in Figure 6a. The patternator data is believed to be accurate to within  $\pm 12\%$  of the actual volume flux based on integrated flow measurements. These results are similar to those obtained with the less dense spray at atmospheric back pressure. The PDPA measured volume flux agrees fairly well with the patternator measurements except at the center of the spray where volume flux is greatest. This is probably due to some multiple scattering causing the gate to be falsely triggered. The flow splitter open path length of 3 mm still allows for the presence of some particles in the beam path which will contribute to the multiple scattering background signal. Some improvement in agreement at the centerline of the spray might be seen at splitter plate separations of less than 3 mm.

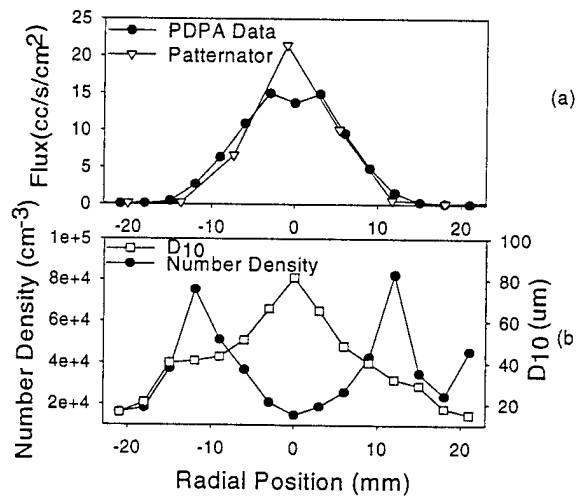


Figure 6: Radial profiles of (a) volume flux and (b) number density and  $D_{10}$  in a very dense spray at  $P_c=416$  psig.

Figure 7 is a comparison between the volume flux measured with a more conventional large probe diameter, with and without the flow splitter, along with

the results presented in Figure 6 for the small probe diameter and flow splitter. Also shown in Figure 7 is the volume flux measured with the patternator. Figure 7 shows a ten fold increase in measured volume flux when using the flow splitter with the larger probe diameter. This was due to an increase in sample validation rate which increased from 25% to 58% at the center of the spray, and a decrease in background scattering which resulted in an increase in the particle count rate. The best agreement with the patternator data is achieved when using the flow splitter in conjunction with the small probe diameter.

The reduction in the background "noise" caused by multiple scattering can clearly be seen in Figure 8, which is an oscilloscope trace of the scattered light signal and gate signal using the flow splitter and small probe diameter for the same spray conditions as in Figure 2 ( $P_c=0$  psig,  $H_2O=18.9$  gm/s,  $N_2=3.17$  gm/s,  $Z=50$  mm). The improvement in signal quality and gate triggering in Figure 8 is a combination of reduction in background signal from multiple scattering and a lower probability of finding more than one particle in the probe volume. The background level is nearly zero and the gate is cleanly triggering on individual droplets identified by the spikes in the scattered light signal.

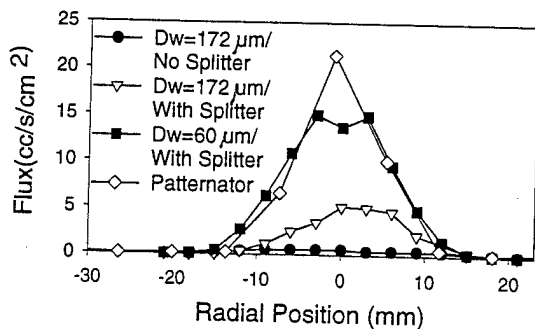


Figure 7: Radial profiles of volume flux for large probe volume with and without flow splitter, and for small probe volume with flow splitter, along with patternator measurements.

### Conclusions

The use of a flow splitter in a dense spray utilizing the phase Doppler interferometry technique has been demonstrated. The flow splitter was found to have a minimal adverse affect on the flowfield. In conjunction with the flow splitter, the PDPA probe volume has been significantly reduced in size. The result is a tremendous improvement in measured volume flux in dense sprays.

The improvement is a result of the reduction in multiple particle occurrences within the probe volume and the reduction in background light due to multiple scattering.

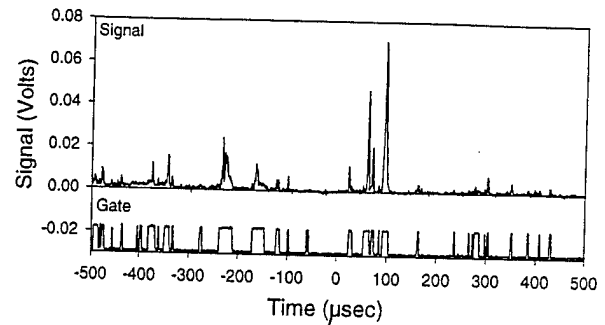


Figure 8: Oscilloscope trace of signal and gate,  $P_c=0$  psig,  $H_2O=18.9$  gm/s,  $N_2=3.17$  gm/s,  $Z=50$  mm,  $R=0$  mm. Beam waist,  $D_w=60$  µm, slit,  $D_s=50$  µm.

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